Heavy quark production and energy loss

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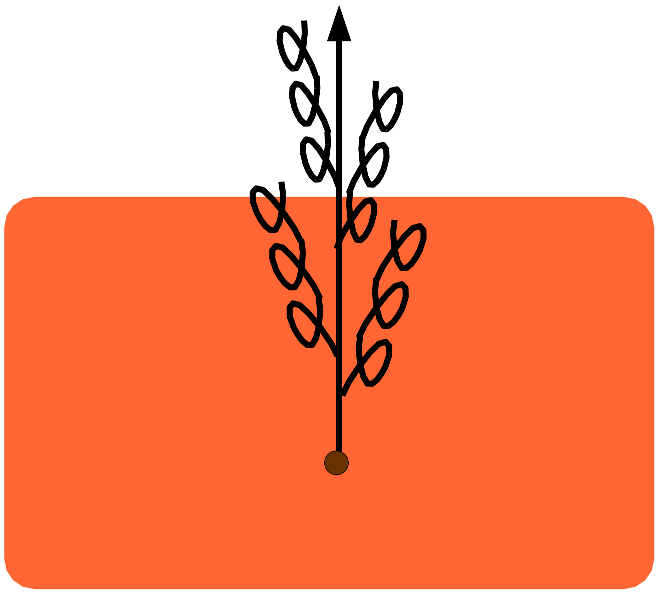
Jet quenching



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  - Problems: surface emission, trigger bias...

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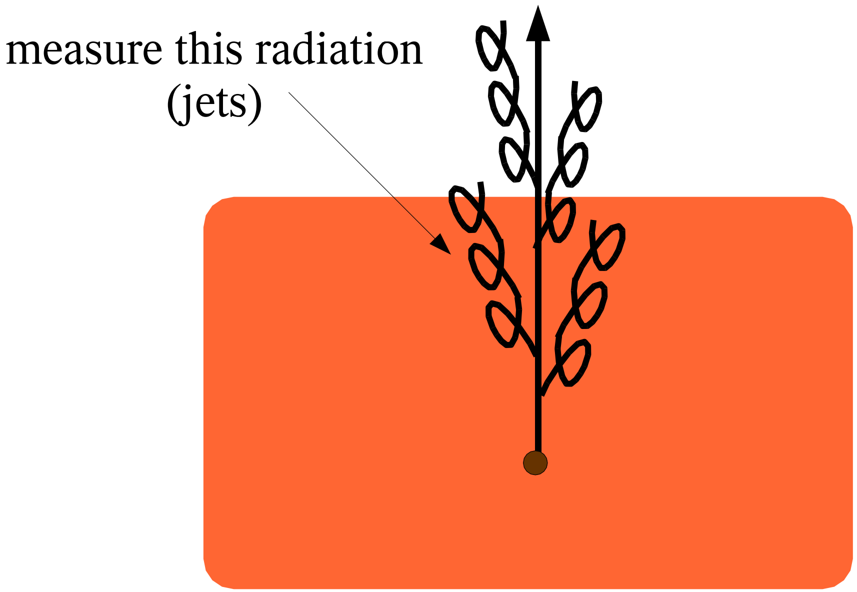

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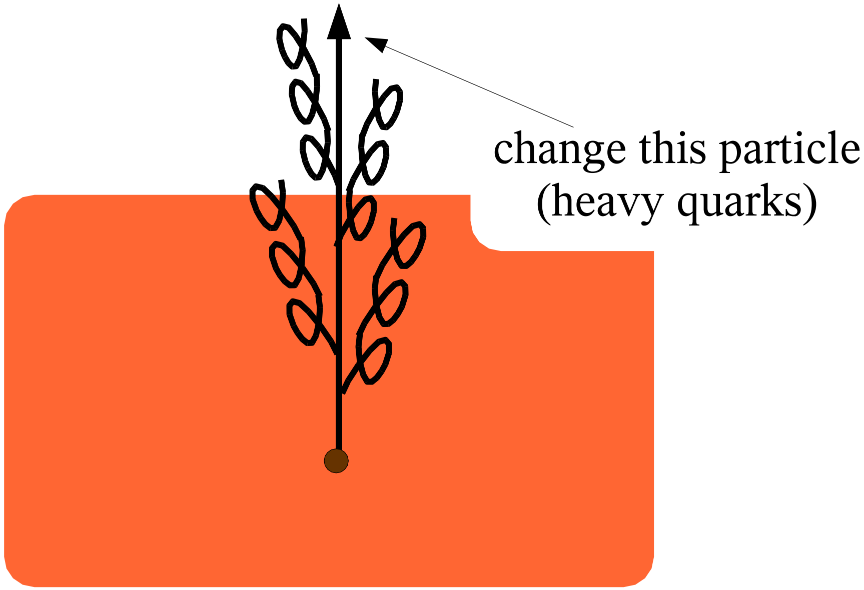
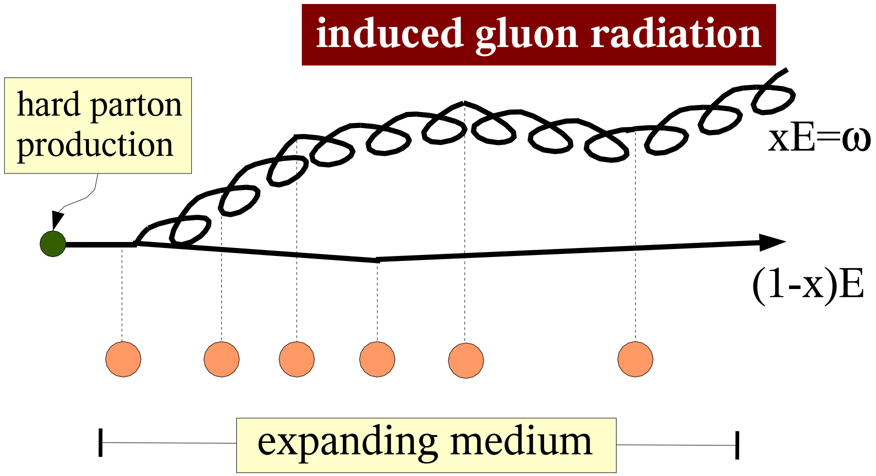


- Suppression of light particles at high-p_t observed at RHIC.
  - Well described by energy loss due to medium-induced gluon radiation
  - Problems: surface emission, trigger bias...
- Measure the structure of radiated particles $\rightarrow$ jets
- Change the composition of the primary $\rightarrow$ heavy quarks

Massless case

Medium–induced gluon radiation (m=0)

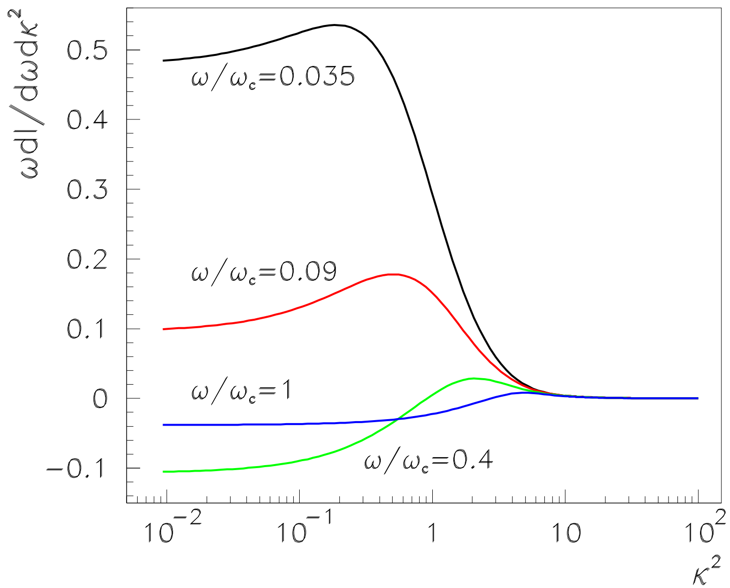


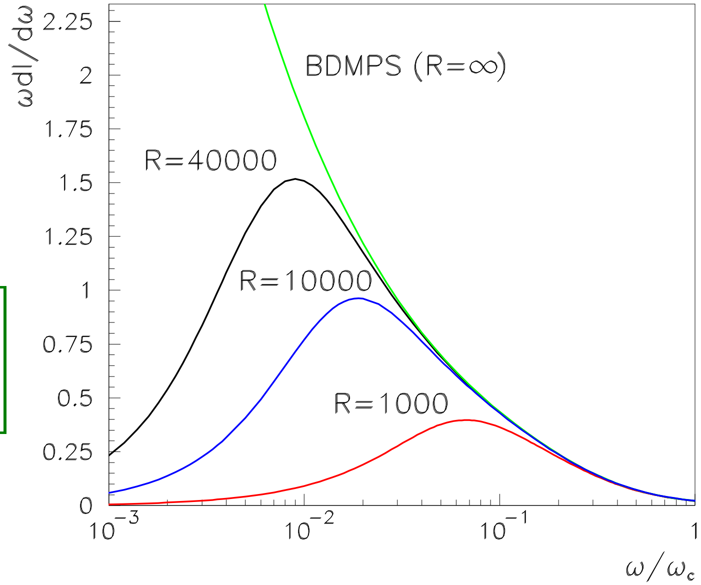
Medium properties: length L, transport coefficient $\hat{q} \sim \frac{\mu^2}{\lambda}$

⇛ $k^2_{\perp,\,\max} \sim \hat{q}L$; $\boxed{\kappa^2 \equiv k^2_\perp/\hat{q}L}$

⇛ Accumulated phase

$$\varphi = \left\langle \frac{k^2_\perp}{2\omega}\Delta z \right\rangle \sim \kappa^2 \frac{\omega_c}{\omega}; \quad \boxed{\omega_c \equiv \frac{1}{2}\hat{q}L^2}$$





Rad. suppressed by coherence

$$\varphi \lesssim 1 \Longleftrightarrow \kappa^2 \lesssim \omega/\omega_c$$

Angular distribution

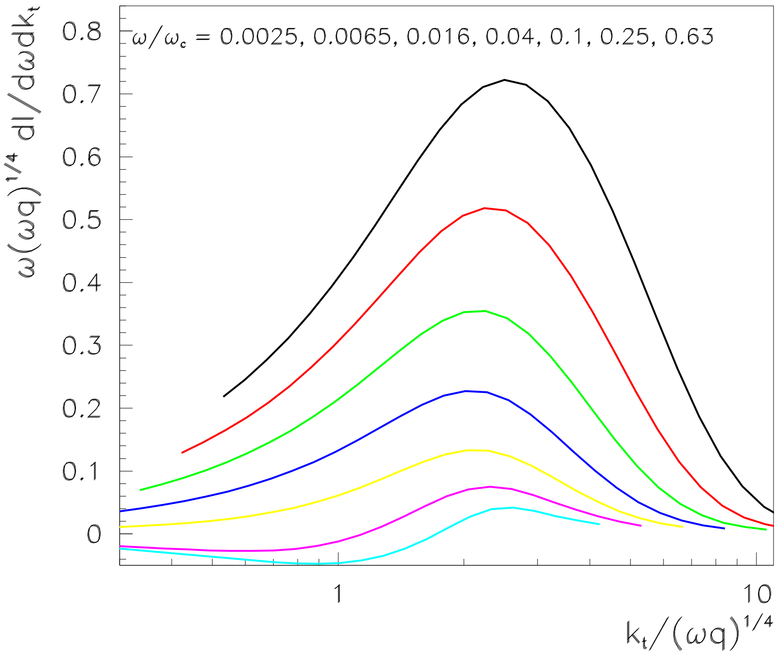
The same spectrum in different variables ω/ω_c, $k_t^2/\sqrt{\omega\hat{q}}$

Heuristic argument

$$t_{\rm form} \sim \frac{\omega}{k_t^2} \quad k_t^2 \sim \mu^2 \frac{t_{\rm form}}{\lambda}$$

The transport coefficient is defined as $\hat{q} = \frac{\mu^2}{\lambda}$

$$k_t^2 \sim \hat{q}\, t_{\rm form} \quad \Longrightarrow \quad k_t^2 \sim \sqrt{\omega\hat{q}}$$

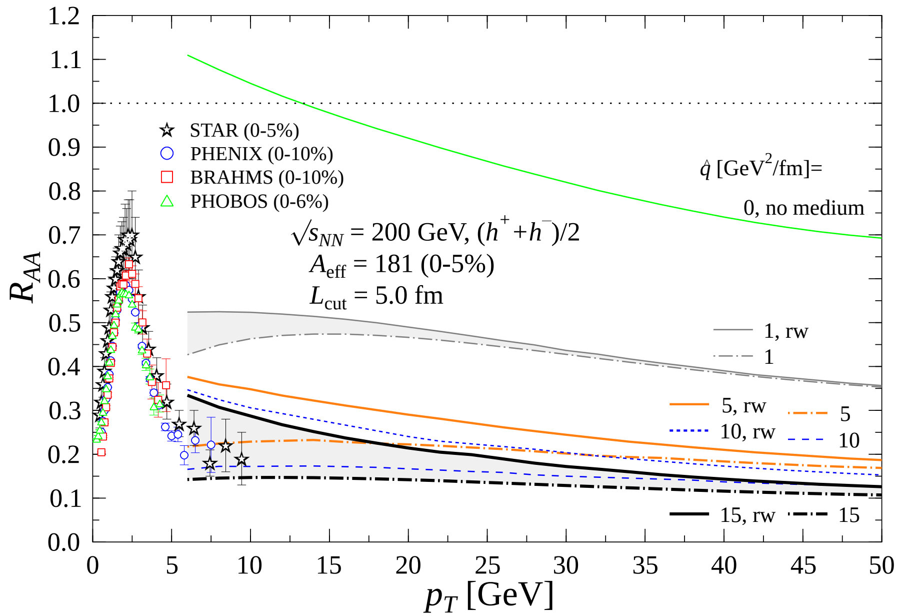


So the radiation is suppressed for

$$\sin\theta \lesssim \sqrt{\sqrt{\frac{\hat{q}}{\omega^3}}}$$

Application of the formalism

$$d\sigma_{(\mathrm{med})}^{AA\to h+X} = \sum_f d\sigma_{(\mathrm{vac})}^{AA\to f+X} \otimes P_f(\Delta E, L, \hat{q}) \otimes D_{f\to h}^{(\mathrm{vac})}(z, \mu_F^2)\,.$$



[Eskola, Honkanen, Salgado, Wiedemann (2004)]

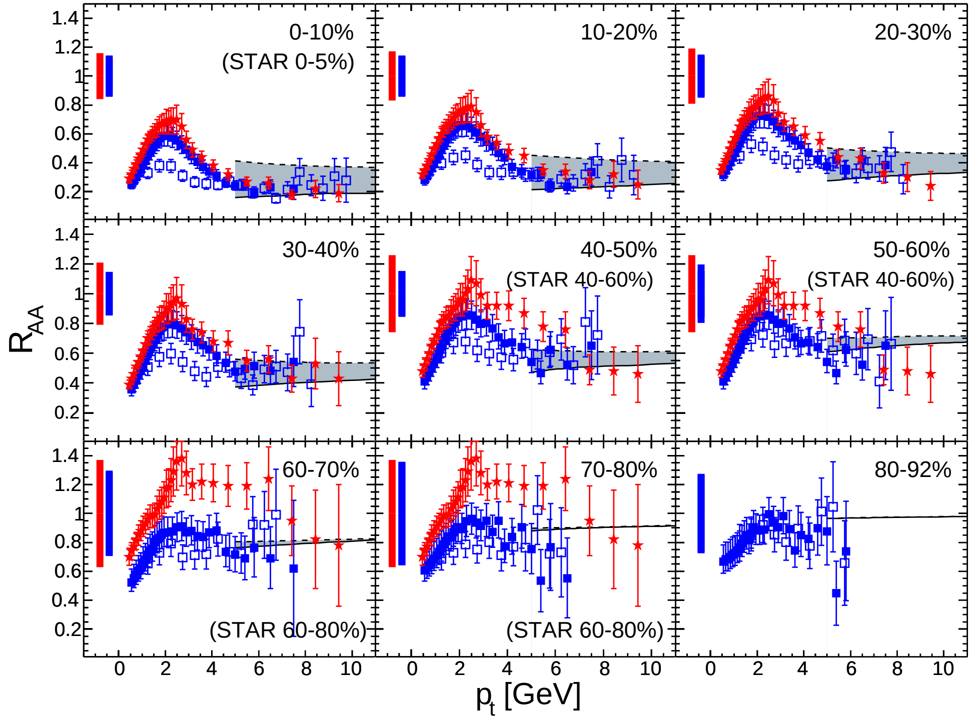
⇛ Data favors a large time-averaged transport coefficient

$$\hat{q} \sim 5 \ldots 15 \frac{GeV^2}{fm}$$

[Many other groups describe these data: Gyulassy, Levai, Vitev, Wang, Drees, Feng, Jia, Arleo, Dainese, Loizides, Paic...]

Centrality dependence

$\hat{q} \propto$ density



[Dainese, Loizides, Paic (2005)]

Opacity problem

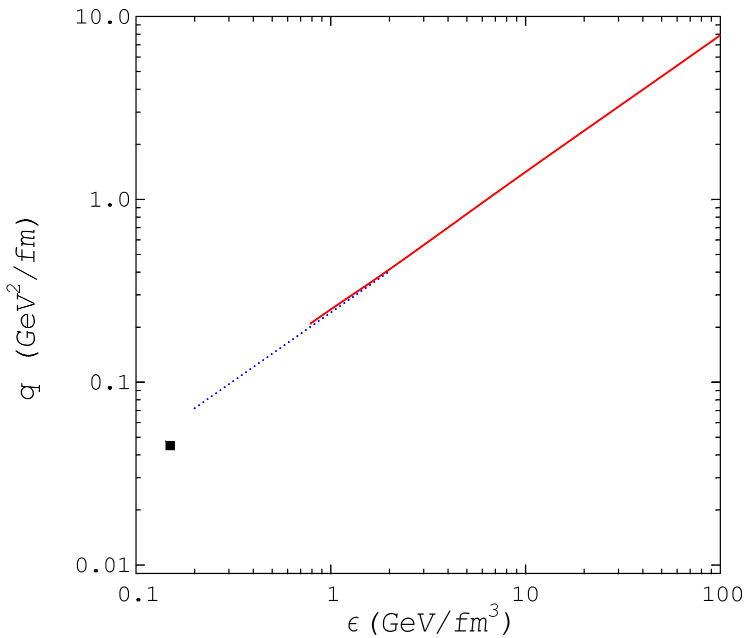
- $\hat{q} = c\epsilon^{3/4}$ for an ideal QGP $c_{ideal}^{QGP} \sim 2$
- We obtain [Eskola, Honkanen, Salgado, Wiedemann (2004)]

$$\bar{\hat{q}} = \frac{2}{L^2}\int_{\tau_0}^{\tau_0+L} d\tau(\tau-\tau_0)\hat{q}(\tau) \Longrightarrow$$

$$c = \frac{\hat{q}}{\epsilon^{3/4}(\tau_0)}\frac{2-\alpha}{2}\left(\frac{L}{\tau_0}\right)^{\alpha} \Rightarrow \boxed{c > 5c_{ideal}^{QGP}}$$

[taking $\epsilon(\tau_0) < 100\frac{\text{GeV}}{\text{fm}^3}$, $L/\tau_0 \sim 10$, $\alpha = 1$]

- Remember $\hat{q}$ proportional to the density times cross section $\Rightarrow$



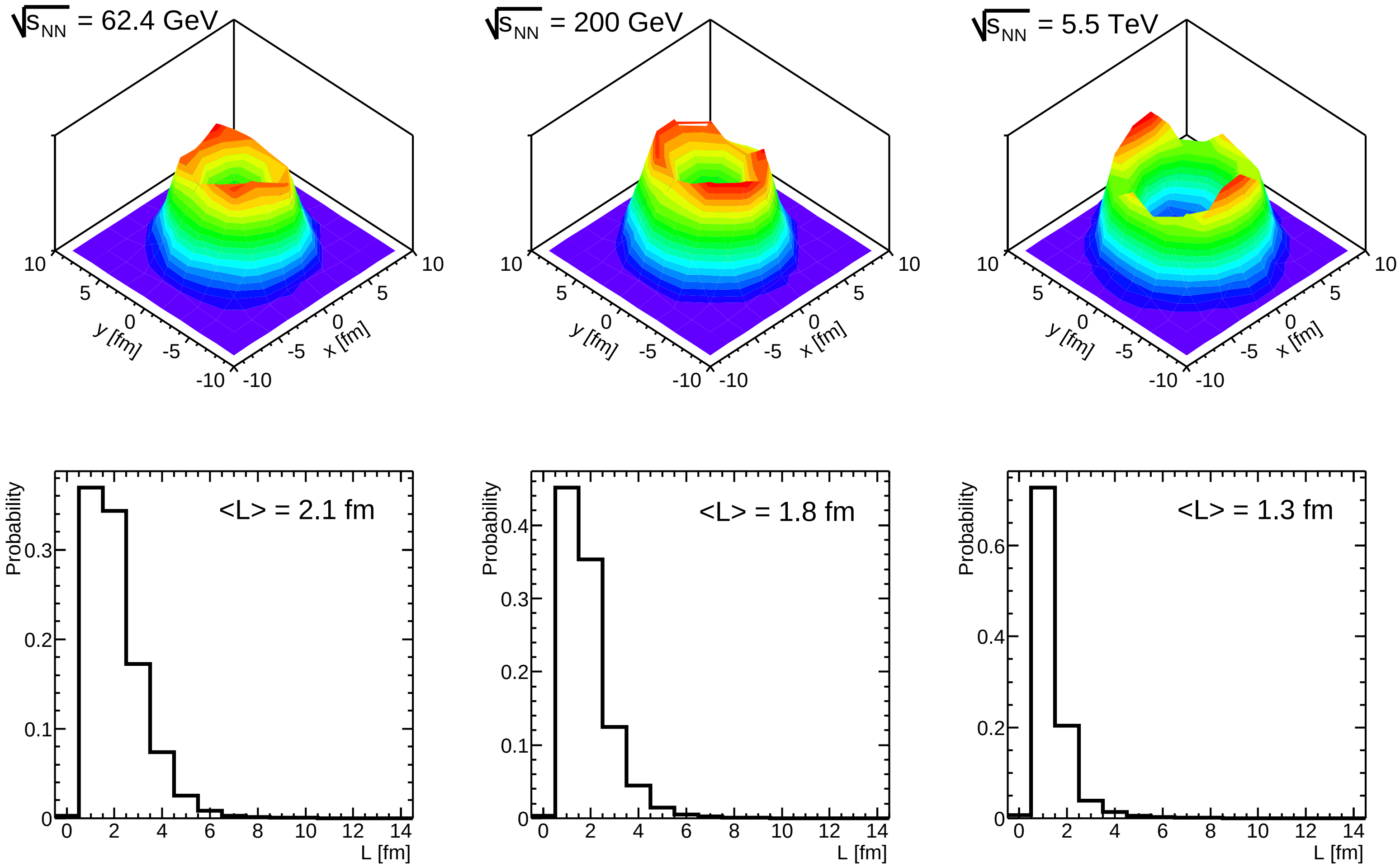
[Baier 2002]

The interaction of the hard parton with the medium is much stronger than expected.

Corona effect

The medium produced at RHIC is so dense that only particles produced close to the surface can escape.[Muller (2003)]

[Dainese, Loizides, Paic (2004); Eskola, Honkanen, Salgado, Wiedemann (2004)]



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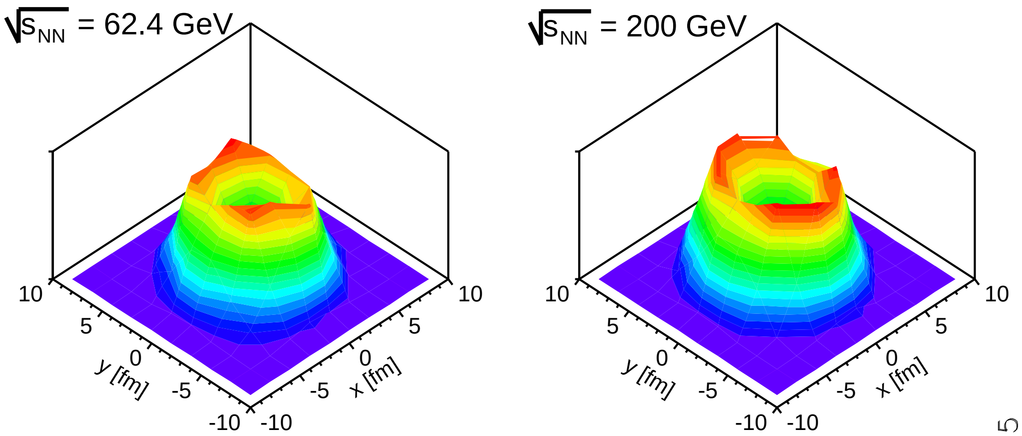
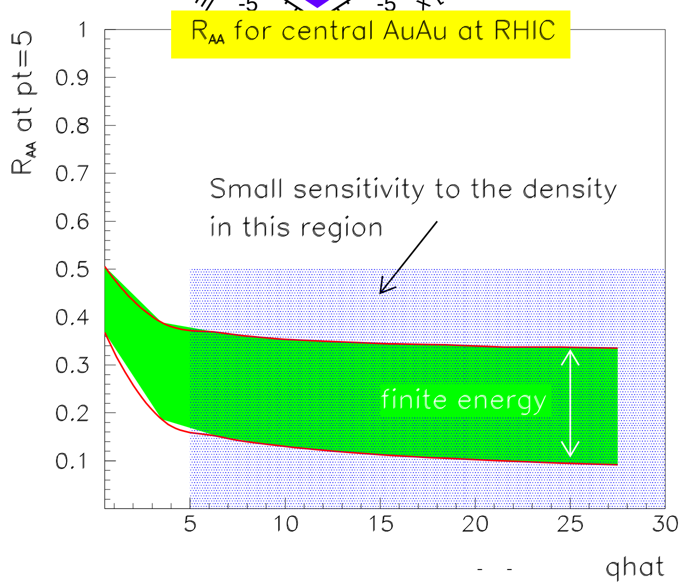


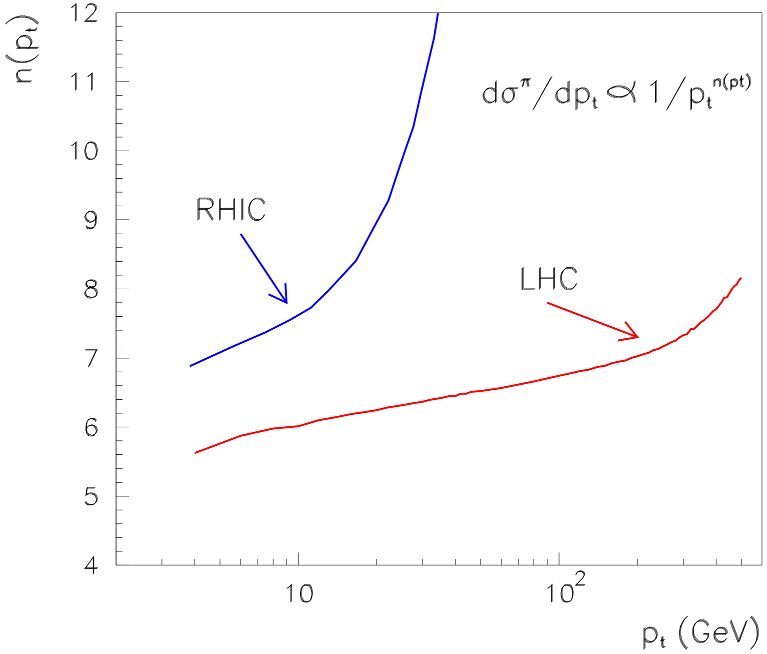
In this case, the sensitivity to $\hat{q}$ becomes small (bad determination of the medium density)

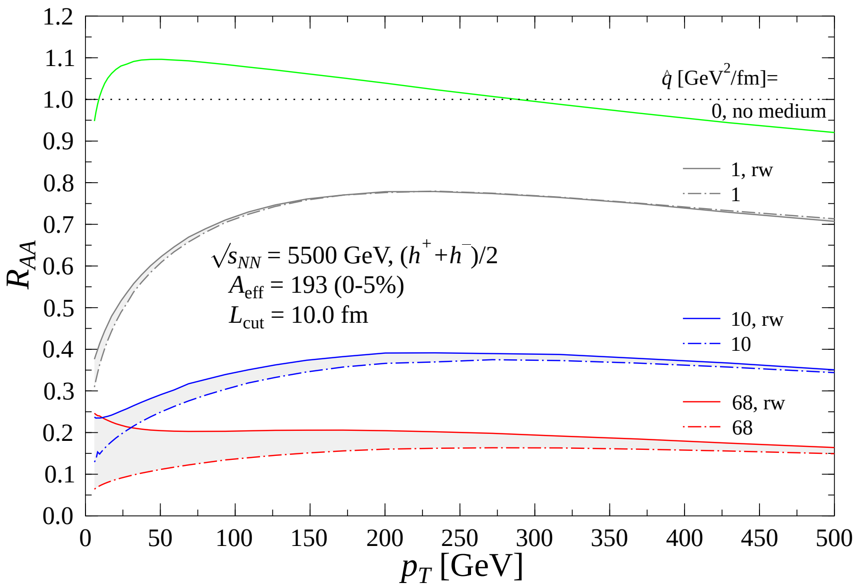


Flatness of the suppression

Trigger bias

⇛ Steepness of the spectrum $\frac{d\sigma}{dp_t} \sim \frac{1}{p_t^n} \Longrightarrow$ small z, ϵ





R_{AA} flat also for the LHC

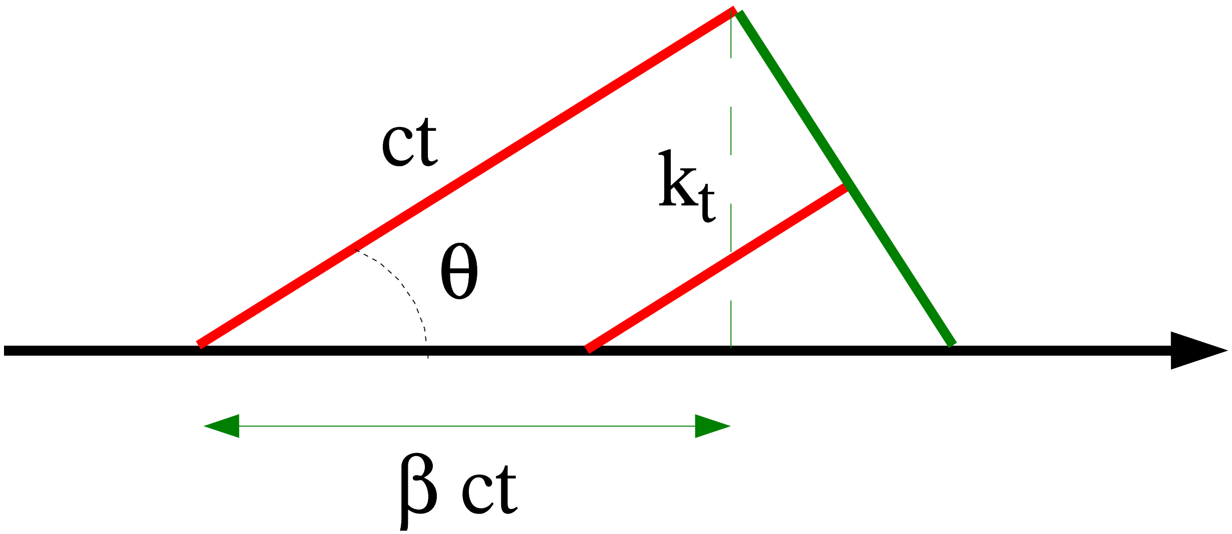
⇛ High-p_t hadrons are fragile objects – more fragile the highest the p_t

[Eskola, Honkanen, Salgado, Wiedemann (2004)]

Heavy quarks

Vacuum radiation: Dead cone effect

$$\sin^2\theta_0 = 1-\beta^2 = \left(\frac{m}{E}\right)^2$$



Dead cone effect Angles smaller than $\theta_0 \equiv m/E$ are suppressed in vacuum radiation [Dokshitzer, Khoze, Troyan (1991)]

$$\omega\frac{dI_{\rm vac}}{d\omega dk_t^2}\sim\frac{1}{k_t^2}\quad\longrightarrow\quad\omega\frac{dI^m_{\rm vac}}{d\omega dk_t^2}\sim\frac{k_t^2}{[k_t^2+\omega^2\theta_0^2]^2}$$

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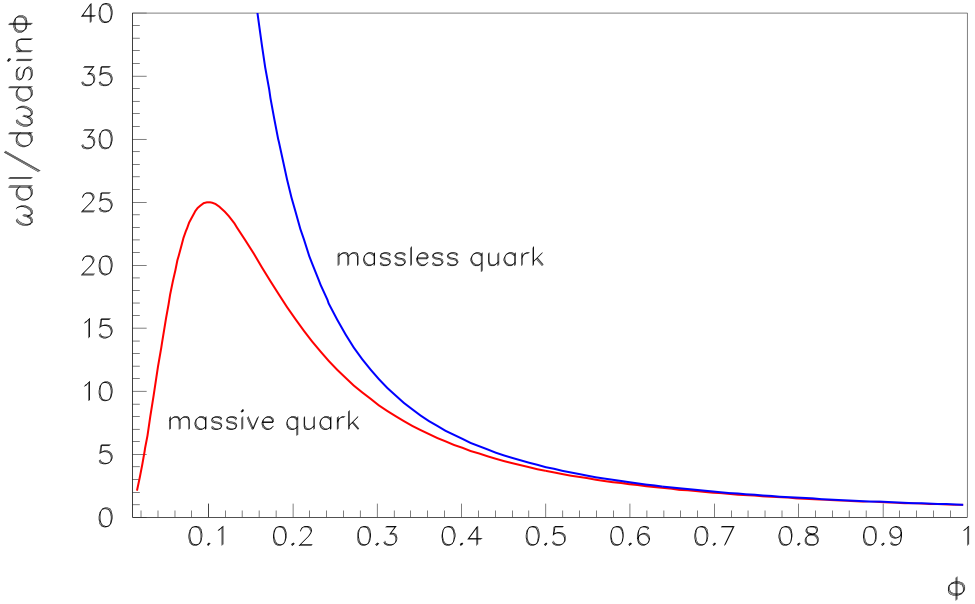

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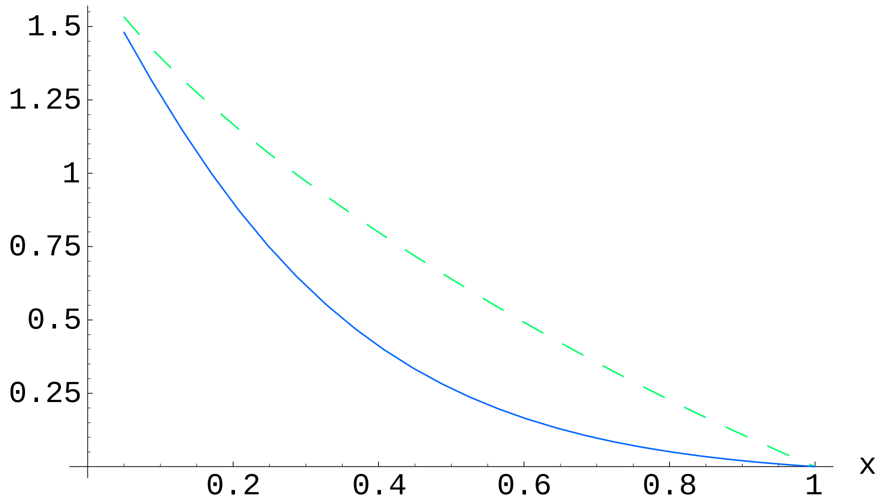
Heavy quark energy loss

- Dokshitzer & Kharzeev 2001 took $\theta \sim \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$

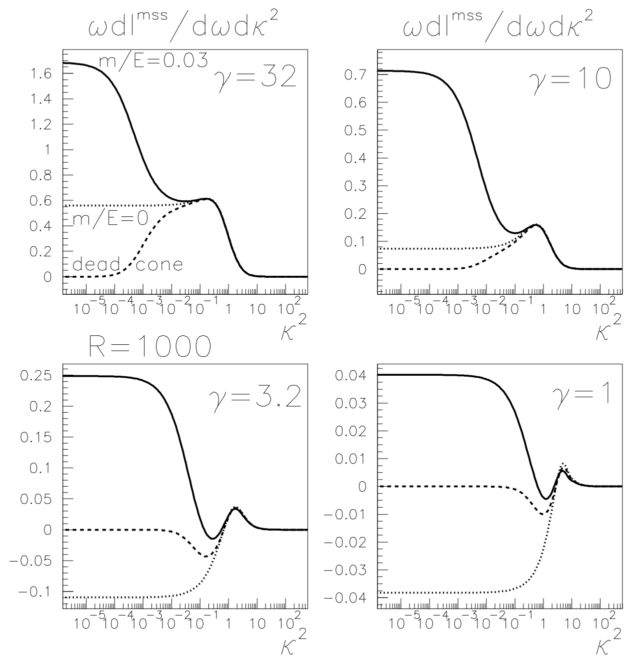
$$\omega \frac{dI_{\rm med}^{\rm mass}}{d\omega} = \frac{1}{\left(1 + \frac{\theta_0^2}{\theta^2}\right)^2} \omega \frac{dI_{\rm med}^{\rm m=0}}{d\omega}$$



- Medium-induced gluon radiation is reduced in the mass case $\Longrightarrow$ less energy loss for heavy than for light quarks.

Medium-induced gluon radiation: massive case

⇒ More refined calculations of the double differential spectrum of heavy quarks reveal a richer structure



[Armesto, Salgado, Wiedemann (2004)]

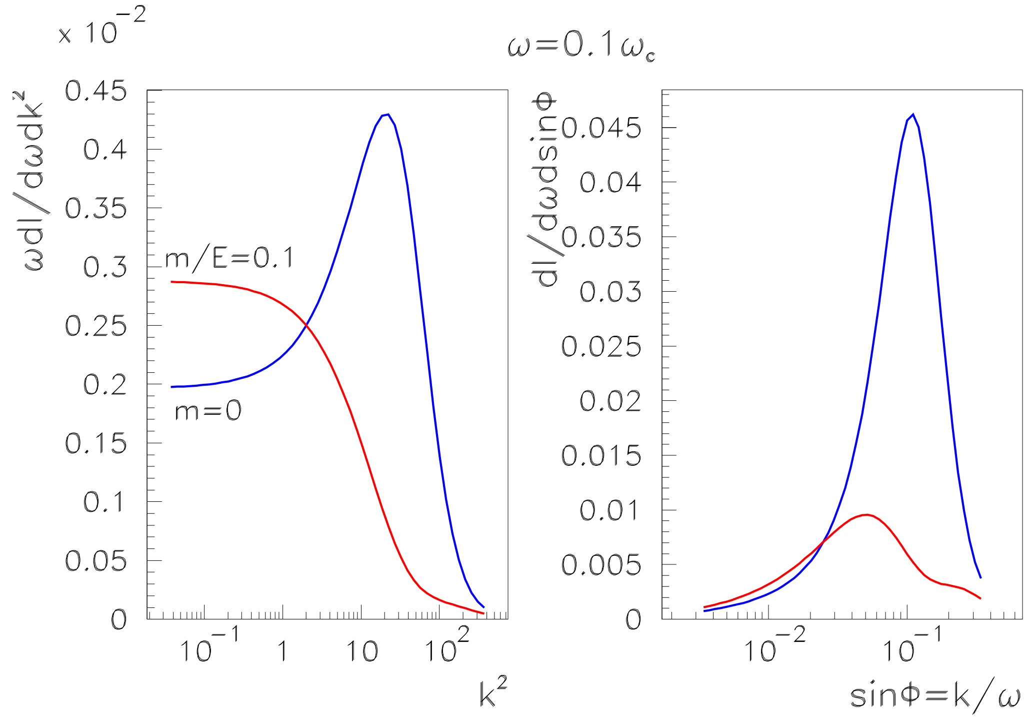
⇒ New phase term in the massive case:

$$\varphi = \left\langle \frac{k_\perp^2}{2\omega}\,\Delta z \right\rangle \longrightarrow \left\langle \frac{k_\perp^2}{2\omega}\,\Delta z + \bar{q}\,\Delta z \right\rangle ;\; \bar{q} \simeq \frac{x^2 M^2}{2\omega} ;\; \left[x = \frac{\omega^2}{E^2} \right]$$

[Similar results: Djordjevic, Gyulassy (2003); Zhang, Wang, Wang (2004)]

Angular distribution

- The angular distribution is modified



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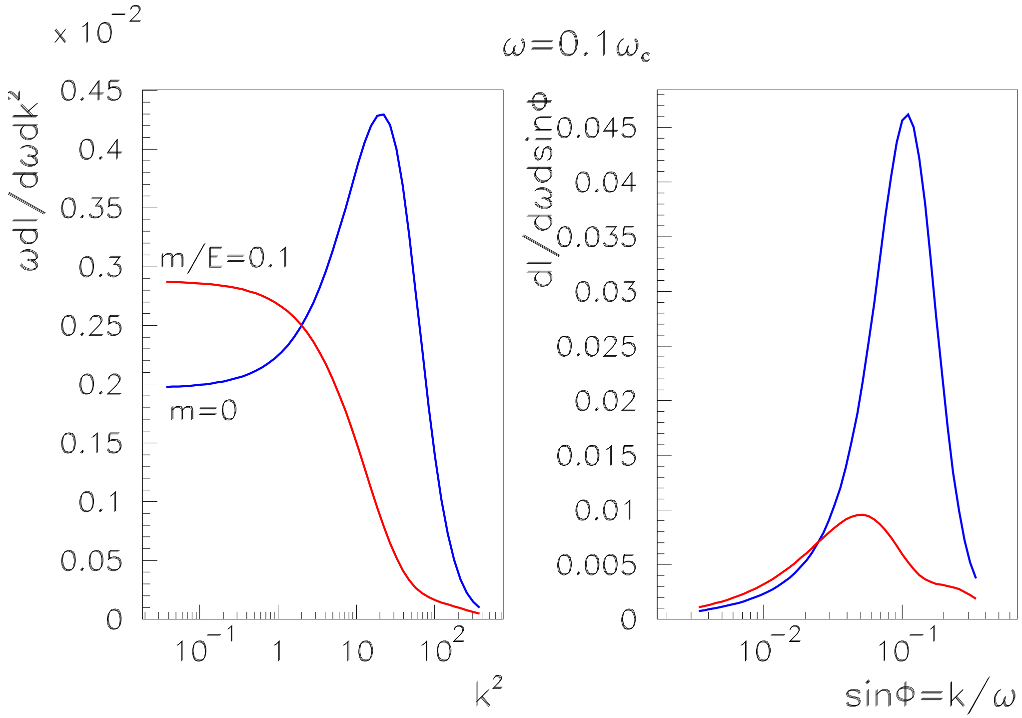
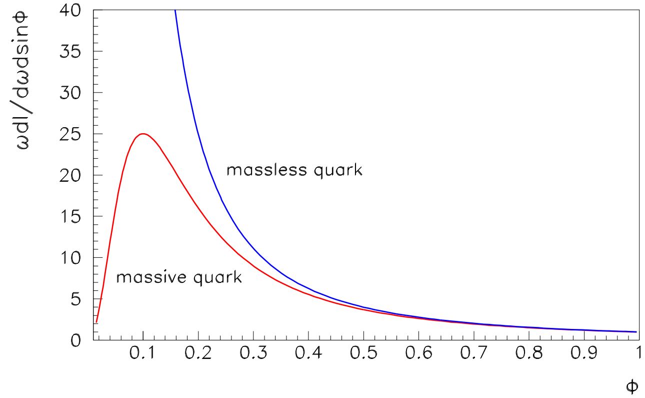




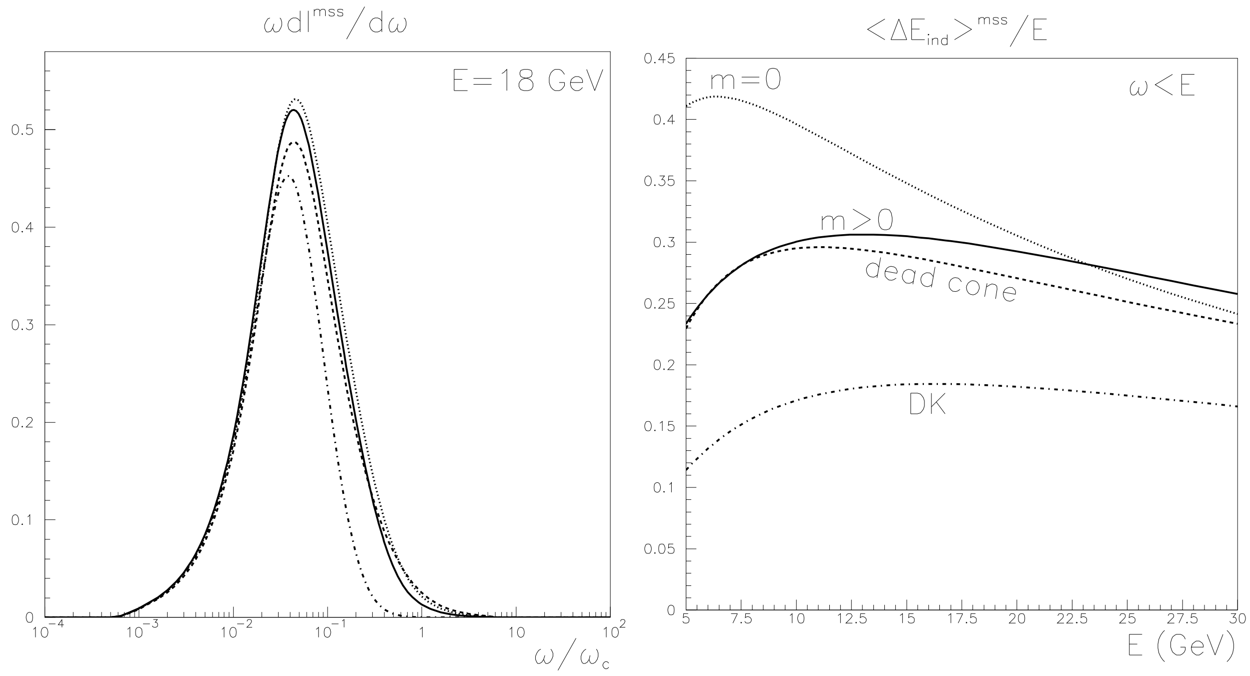
(vacuum)

- The effect of the mass in the medium case is
  - Suppress radiation at large angle
  - Enhance (moderately) at small angle
- Net effect: the energy loss is smaller in the massive case

Energy spectrum

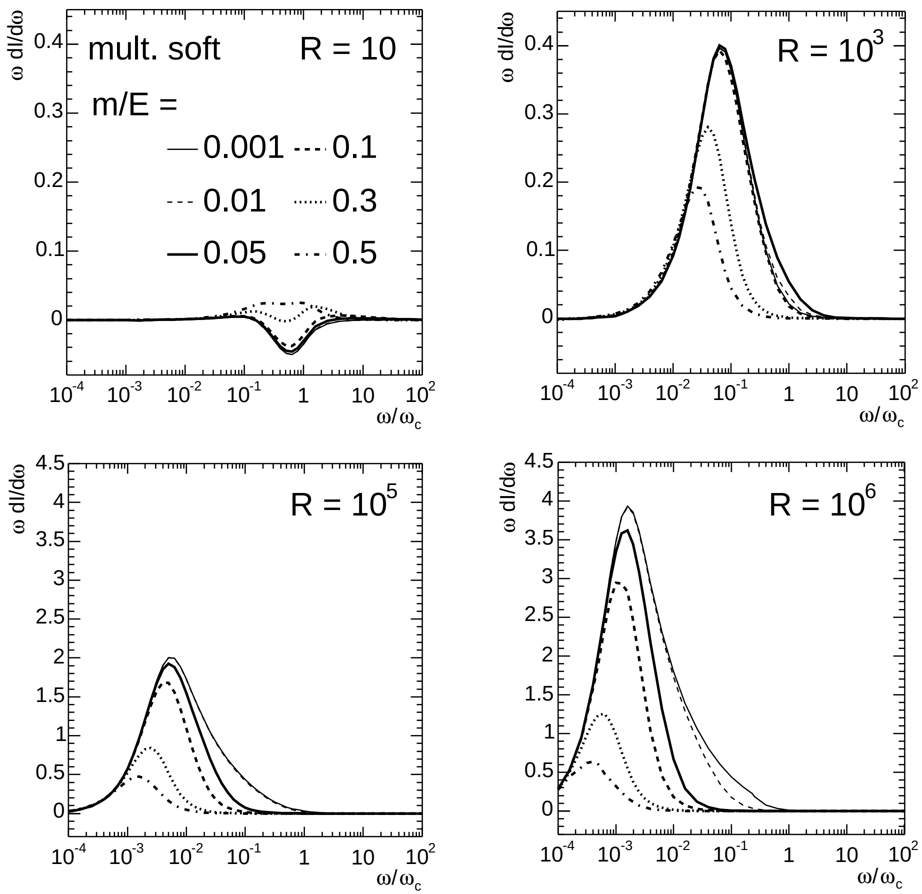
⇛ To compute the energy loss, the energy spectrum is needed

$$\omega \frac{dI}{d\omega} = \int_0^{\omega^2} dk_t^2 \omega \frac{dI}{d\omega dk_t^2}$$



⇛ Smaller energy loss for heavy quarks

Influence of the mass



$$R \equiv \omega_c \, L$$

Notice that the effect of the mass increases with the length L

Practical applications

Formalism

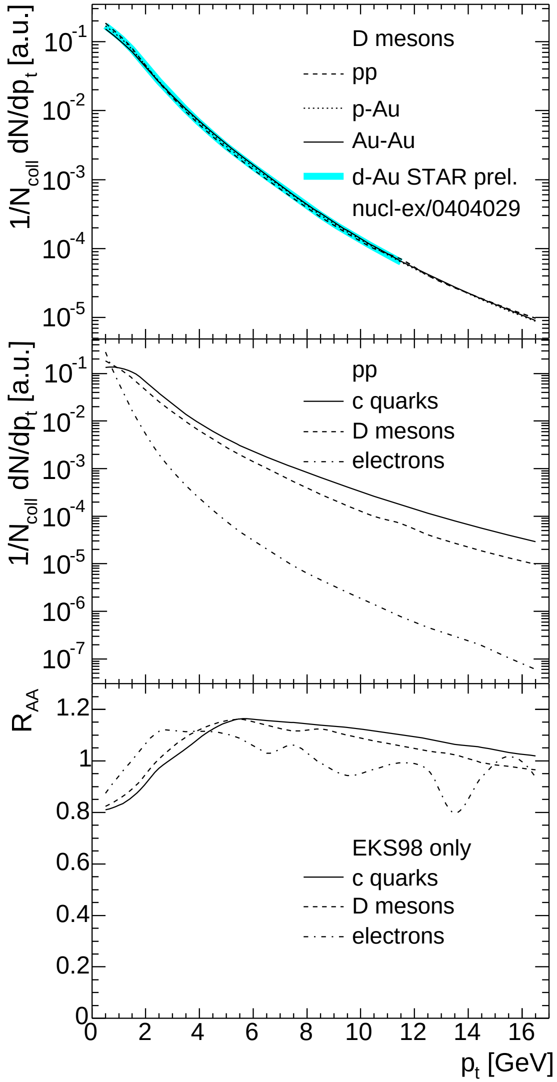
$$d\sigma^{AA\to h+X}_{(\text{med})} =$$
$$d\sigma^{AA\to f+X}_{(\text{vac})} \otimes P\left(\frac{\Delta E}{\omega_c}, R, \frac{m}{E}\right) \otimes D^{(\text{vac})}_{f\to h}$$

- ⇛ $P\left(\frac{\Delta E}{\omega_c}, R, \frac{m}{E}\right)$ probability of losing ΔE due to medium-induced radiation ($R = \omega_c\, L$)
- ⇛ In the vacuum

$$P\left(\frac{\Delta E}{\omega_c}, R, \frac{m}{E}\right) = \delta(\Delta E)$$

- ⇛ We tuned PYTHIA to reproduce the shape of the data from STAR on the D meson p_t distribution in dAu.

  [Armesto, Dainese, Salgado, Wiedemann (2005); Same method as in Dainese, Loizides, Paic (2004)]

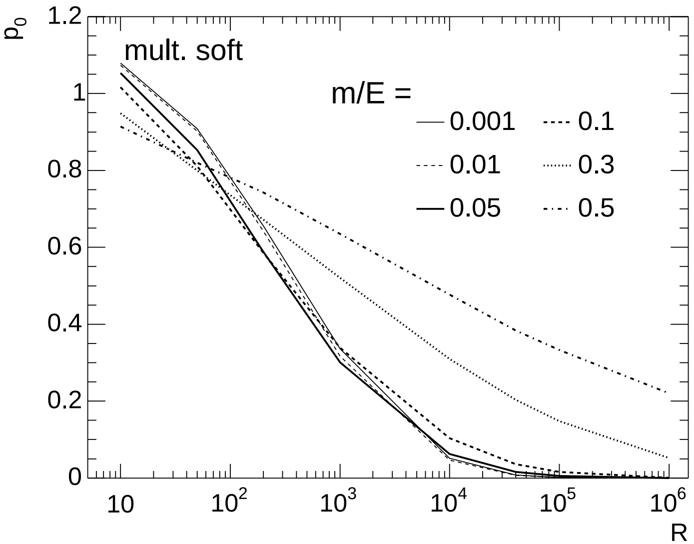


Quenching weights

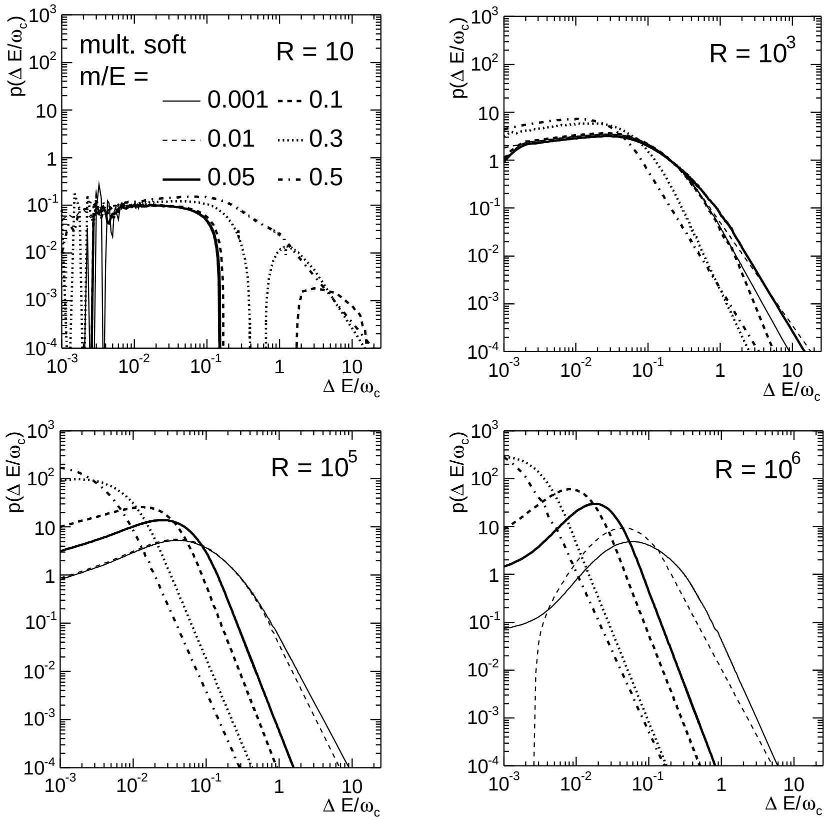
⇛ In the independent gluon emission approximation [Baier *et al* (2001)]

$$P\left(\frac{\Delta E}{\omega_c}, R, \frac{m}{E}\right) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI^{\rm med}(\omega_i)}{d\omega}\right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i\right) \exp\left[-\int d\omega \frac{dI^{\rm med}}{d\omega}\right]$$

probability of no-energy loss



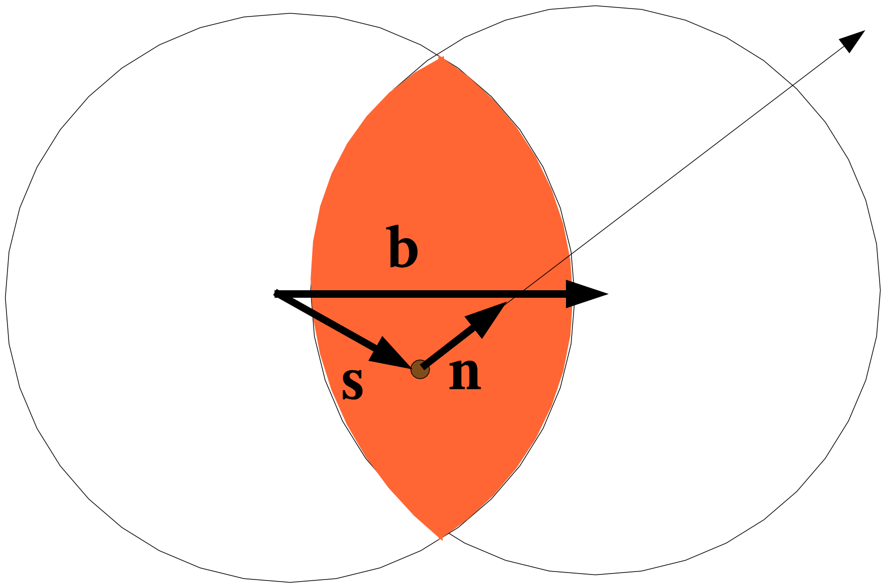
$$R \equiv \omega_c \, L$$



[Armesto, Dainese, Salgado, Wiedemann (2005)]

[tabulated in: http://www.pd.infn.it/˜dainesea/qwmassive.html]

Geometry

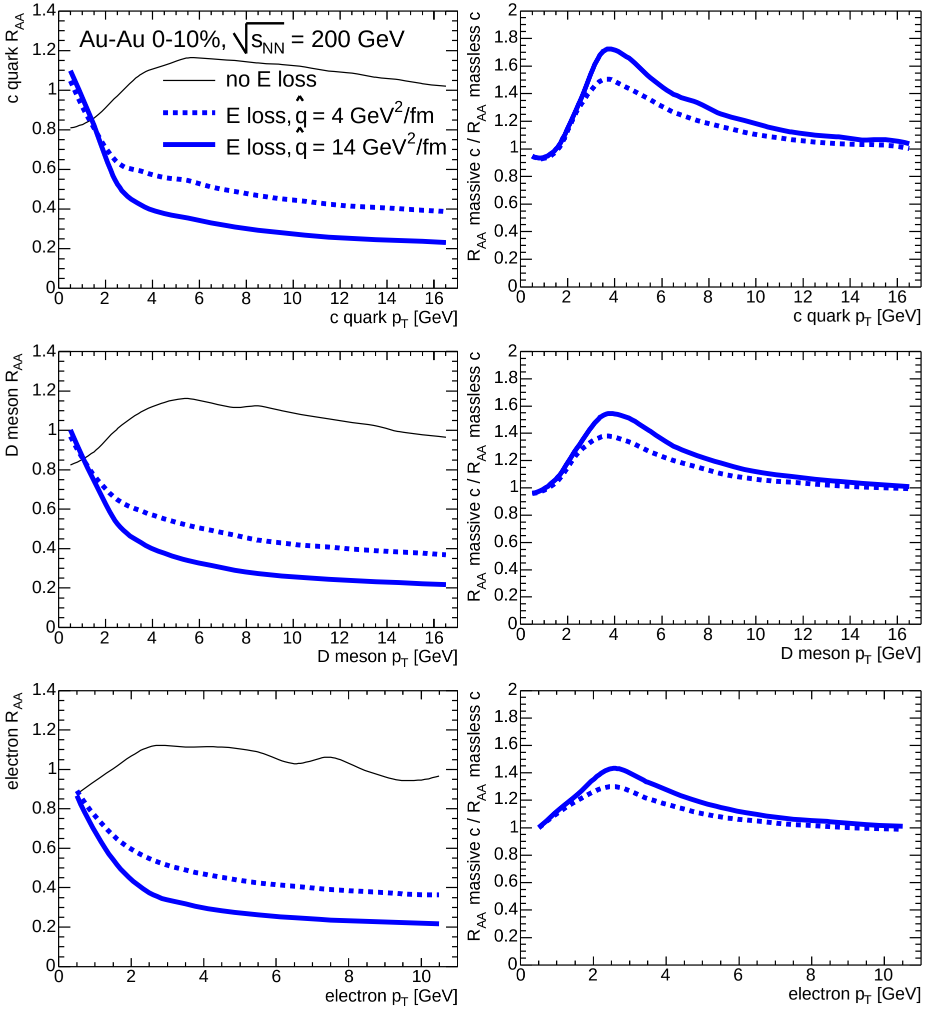


$$\hat{q}(\xi) = kT_A(\mathbf{s} + \xi\mathbf{n})T_B(\mathbf{b} - [\mathbf{s} + \xi\mathbf{n}])$$

$$\omega_c = \int_0^\infty d\xi\, \xi\, \hat{q}(\xi)\ ; \quad R = \frac{2\omega_c^2}{\int_0^\infty d\xi\, \hat{q}(\xi)}$$

[Dainese, Loizides, Paic (2004); Armesto, Dainese, Salgado, Wiedemann (2005)]

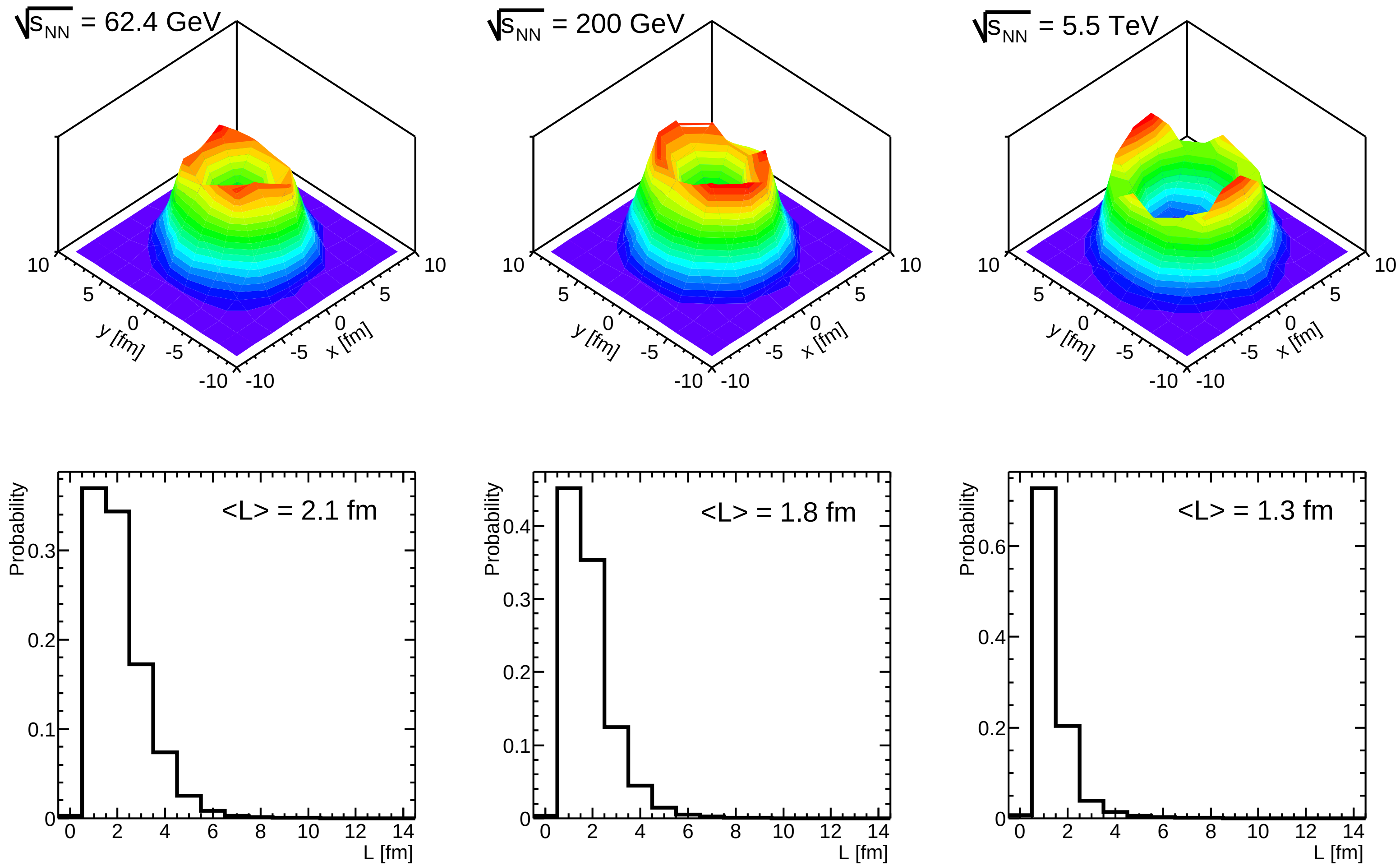
Results for RHIC



[Armesto, Dainese, Salgado, Wiedemann (2005)]

Surface emission with mass terms

- Suppression for charm and light quarks very similar unexpected?
- Remeber that mass effects small for small lenghts



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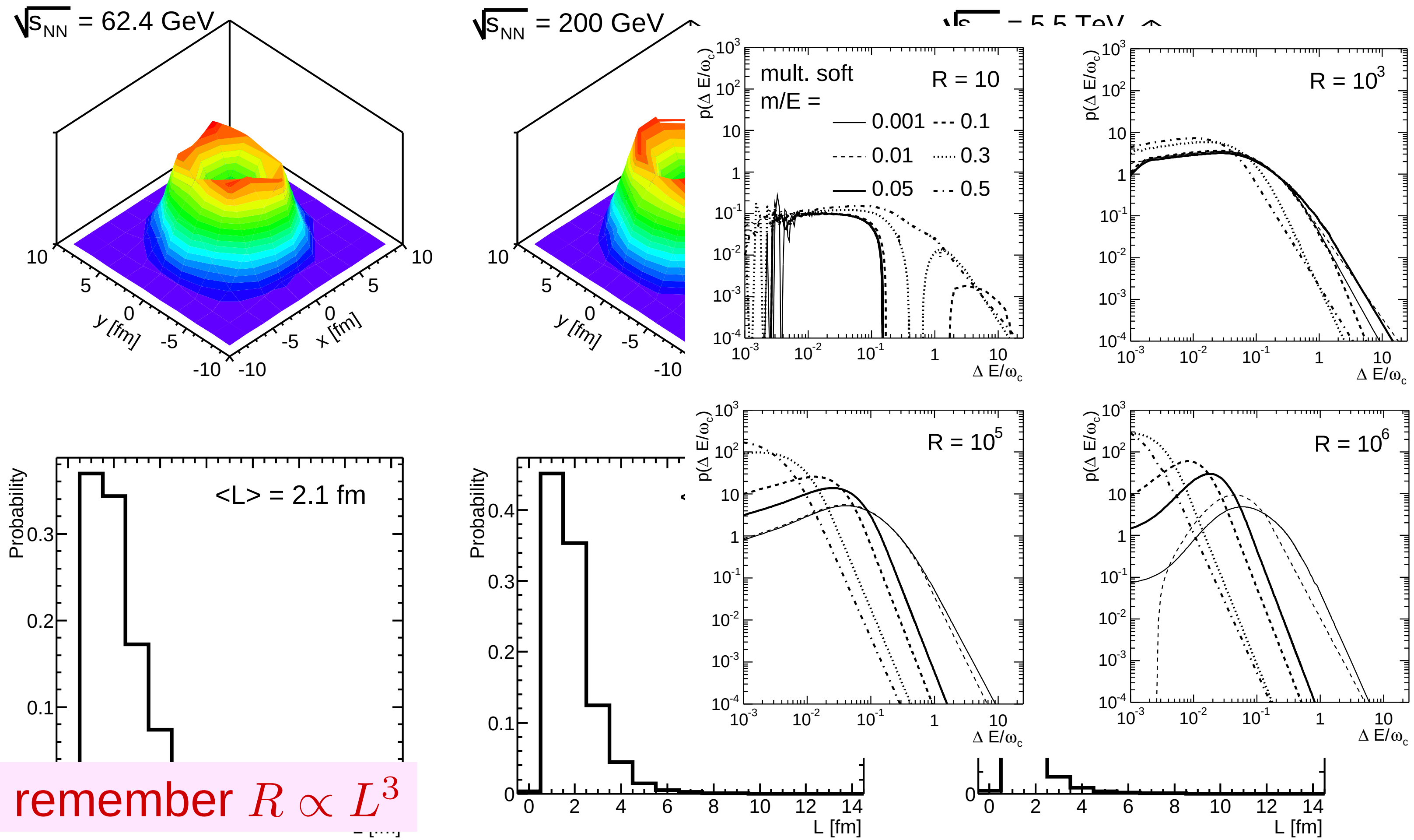
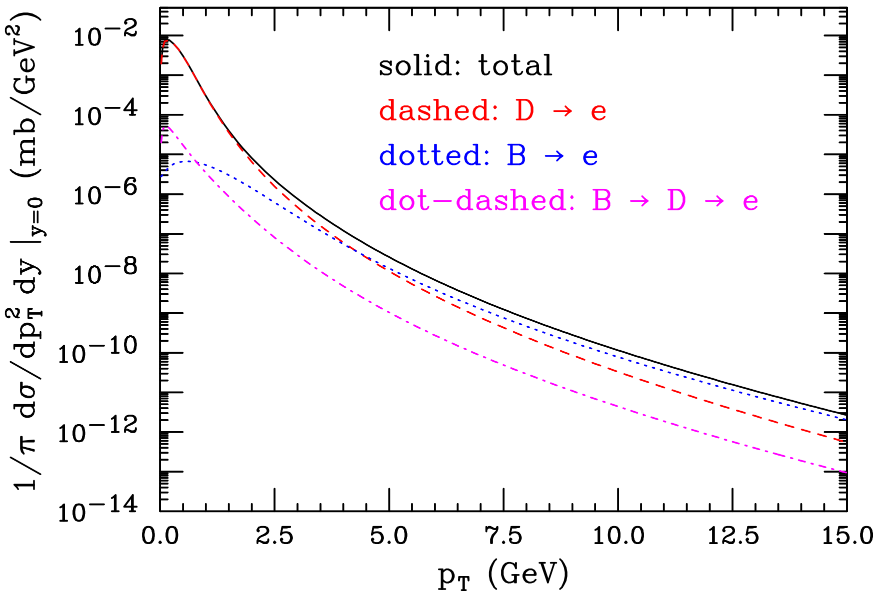
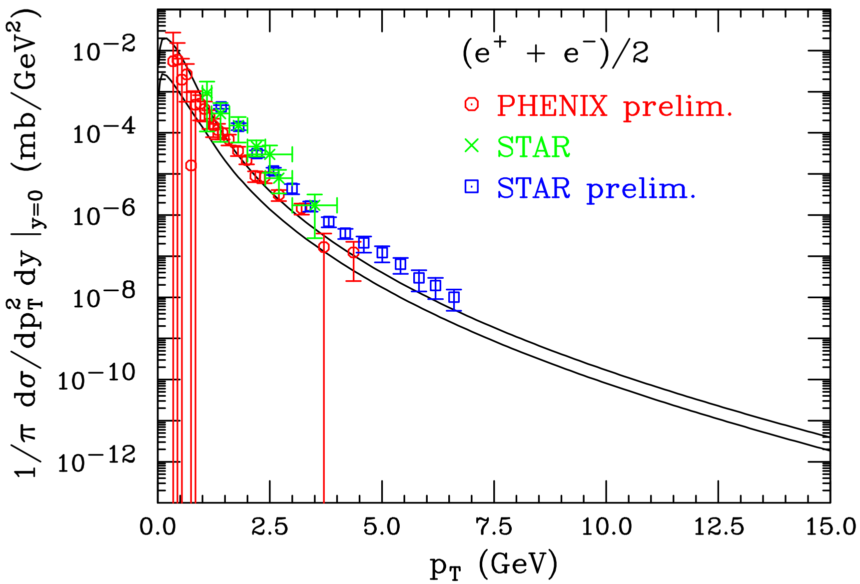


remember $R \propto L^3$

Influence of B mesons

- The electrons measured have contributions from the decay of B mesons

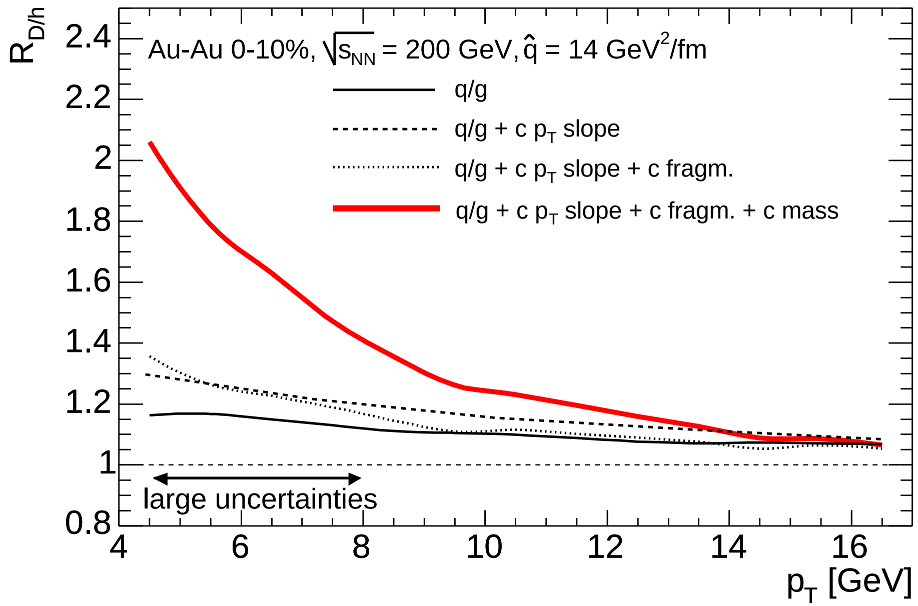




[Cacciari, Nason, Vogt (2005)]

- B-meson decays dominate for $p_t \gtrsim 5 \ldots 6$ GeV
- The correlation between the momentum of the HQ and the electron is very smeared

Massive over light particle ratio



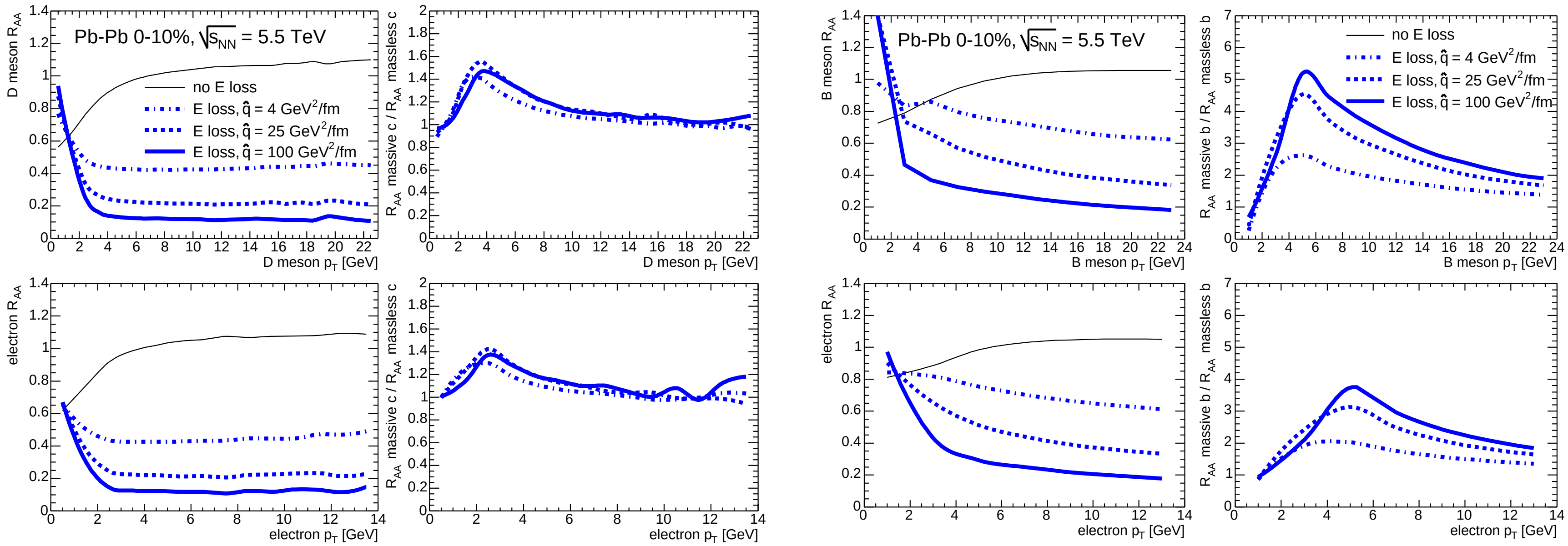
[Armesto,Dainese,Salgado,Wiedemann 2005]

- Quark vs gluon energy loss: $\Delta E^g = N_C/C_F \Delta E^{q,\mathrm{m}=0}$
  - Increases $R_{D/h}$
- Light-particle spectrum slope larger than massive one
  - Increases $R_{D/h}$
- charm fragmentation harder
  - Decreases $R_{D/h}$
- Heavy quark suppression of gluon radiation ('dead-cone')
  - Increases $R_{D/h}$

Extrapolations to the LHC

⇛ Extrapolation according to the expected density ($\hat{q} \propto$ density)

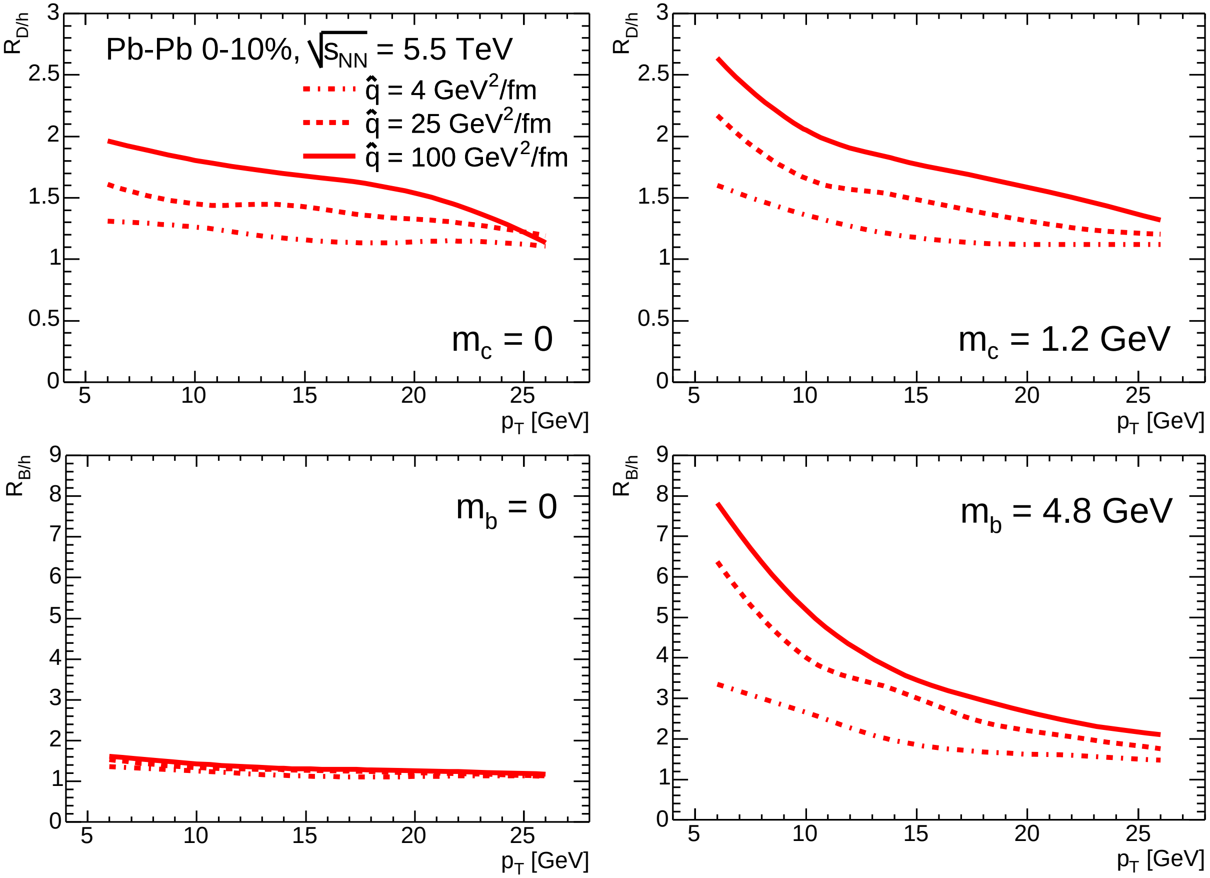
⇛ We take a factor 7 from Eskola *et al* (2000) [probably too large]



[Armesto, Dainese, Salgado, Wiedemann (2005)]

Heavy-to-light ratios at the LHC

⇛ D/h and B/h ratios for the LHC



[Armesto, Dainese, Salgado, Wiedemann (2005)]

Conclusions

- Medium-induced gluon radiation is the standard explanation of high-p_t inclusive particle suppression.
  - Several trigger bias effects limit its sensitivity to the medium properties
- Study heavy quarks
  - Different particle composition $N_c/C_F = 2.25$
  - Softer perturbative slope
  - Harder fragmentation
  - Smaller medium-induced radiation
- Mass effects in agreement with RHIC data but in dangerous region
  - Surface emission makes the mass effect smaller
- LHC will be able to measure mass effects in a large p_t range with B mesons